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# FABRICATION AND REPLICATION OF CONTINUOUS-RELIEF DOEs

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## ABSTRACT

Progress in the fabrication of continuous-relief Diffractive Optical Elements (DOEs) by laser beam writing in photoresist followed by replication into epoxy or polymer materials is described. The technology enables a wide range of microoptical elements to be fabricated, including kinoform elements and general microrelief phase structures for a variety of applications in optical systems. Replicas are produced in polymer foil, as well as in thin epoxy films on glass substrates, using Ni shims generated from the recorded microrelief structures. The continuous relief micro-optical elements offer an interesting alternative to multilevel 'binary' optical elements, in many cases with improved performance and lower cost.

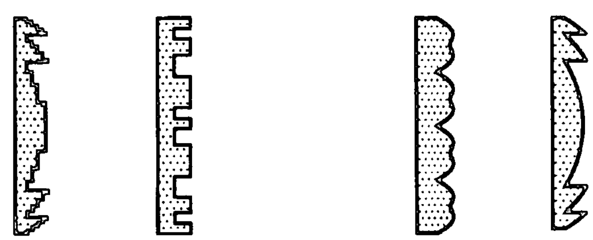
## INTRODUCTION

Surface-relief (DOEs), with typical relief amplitudes of in the micrometer range, are of great interest because they have the potential for low cost mass-production by replication techniques. They can be designed and realised as two basic types (see Figure 1):

**Binary Optical DOEs** : 2-level or multi-level surface-relief microstructures, typically fabricated by semi-conductor fabrication technology, are commonly referred to as *binary optical* elements (from the binary mask lithography used for the fabrication) (1,2).

Binary optical elements for visible wavelengths typically have between 2 and 16 relief levels with sub-micron relief steps, and can require a fabrication technology with a mask alignment accuracy of up to 0.05 µm and a resolution of 0.5 µm. Continuous improvements in design and fabrication technology have led to a considerable potential for this technology, with initial applications in the infrared (the coarser structures are easier to fabricate) and now moving into the visible. Dammann gratings, in which a complex binary or multilevel profile within the grating period generates a specific energy distribution within the diffraction orders, can be used as beam splitters and fan-out elements

**Continuous-relief DOEs** : Diffractive optical elements fabricated as continuous relief microstructures offer a number of very interesting design and performance possibilities (they become identical to binary optical microstructures as the number of levels in the latter tends to infinity). In contrast to binary optics, the fabrication of continuous-relief DOEs generally involves technologies which are not widespread in industry. At the Paul Scherrer Institute in Zürich (PSIZ), laser writing in photoresist has been developed for the flexible fabrication of continuous-relief DOEs with a wide range of surface-relief profiles (3). Holographic exposure techniques can be used for fabricating some microstructures, but are in general very limited in applications.



**Binary Optical DOEs**
Fabrication by binary semiconductor mask lithography

**Continuous-relief DOEs**
Fabrication by direct laser writing lithography

Figure 1 : Examples of *Binary Optical* and *Continuous-relief* Diffractive Optical Elements (not to scale)

Continuous-relief DOEs, often referred to as *kinoforms*, can be designed to perform operations such as beam fan-out with a very high efficiency (4). Fresnel microlenses with continuous-relief segment profiles optimised for phase considerations (Phase Matched Fresnel Elements (5) are a class of DOEs combining diffractive and refractive behaviour, offering novel optical properties and high efficiency.

In this paper we describe progress in the fabrication of continuous-relief DOEs by direct laser writing in photoresist, followed by the electroplating of a Ni replication shim and replication by embossing or casting techniques. This technology development at PSIZ is aimed towards establishing a capability for the writing of a wide range of DOE surface-relief microstructures, together with the possibility for small scale (at PSIZ) as well as large scale (industrial) production. Examples of recent and current DOE fabrication work are given.

## FABRICATION TECHNOLOGY

Continuous-relief DOEs are fabricated in a 2-step process, first in photoresist by laser writing and then in a more stable polymer or epoxy material by replication techniques.

### Laser writing system

The PSIZ laser writing system, shown in Figure 2, has been described elsewhere (3) and will only be briefly summarised here. The surface-relief microstructure is defined in a data file which can be generated or computed by a variety of design procedures. After combining this data with the resist development characteristic, it is used to control the exposure of a resist-coated substrate, which is xy-raster scanned under a focused HeCd laser beam. The laser beam intensity is synchronously controlled (256-level gray scale) to write a fully programmable, 2-dimensional exposure pattern. Development of the resist then results in a continuous-relief microstructure of the desired surface profile. Continuous relief microstructures, typically up to 3 μm depth and maximally up to 20 μm depth, and size in excess of 50 x 50 mm$^2$ are routinely fabricated with this system.

Characterisation and testing of fabricated DOEs is carried out using a number of techniques. A first check on the modulation depth of the developed resist relief can be made using a linear stylus profilometer to measure either a line section of the microstructure or a calibration pattern written at the side. A more detailed analysis is carried out using an Atomic Force Microscope (AFM) to measure the detailed 2-dimensional surface-relief profile as well as the surface roughness.

The accuracy and quality of the fabricated surface-relief microstructures depends upon a number of factors. With the present writing system, the modulation depth of a microstructure can be realised to about ± 5% (this limit is given by the current stability and reproducibility in the resist coating and development

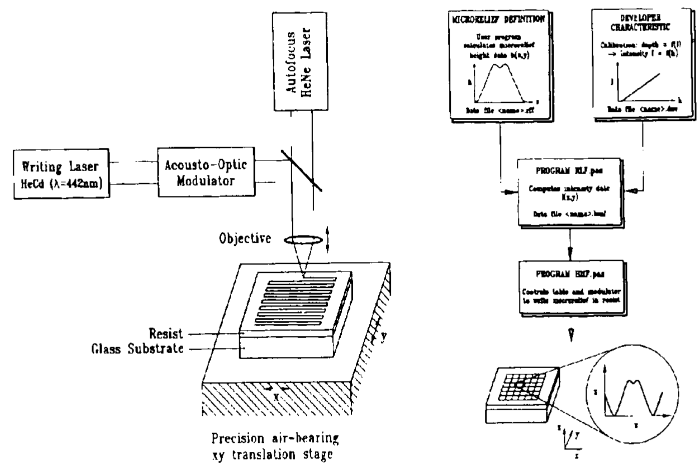



Figure 2 : Laser writing system and software for the writing of continuous-relief DOE microstructures (from Reference 3)

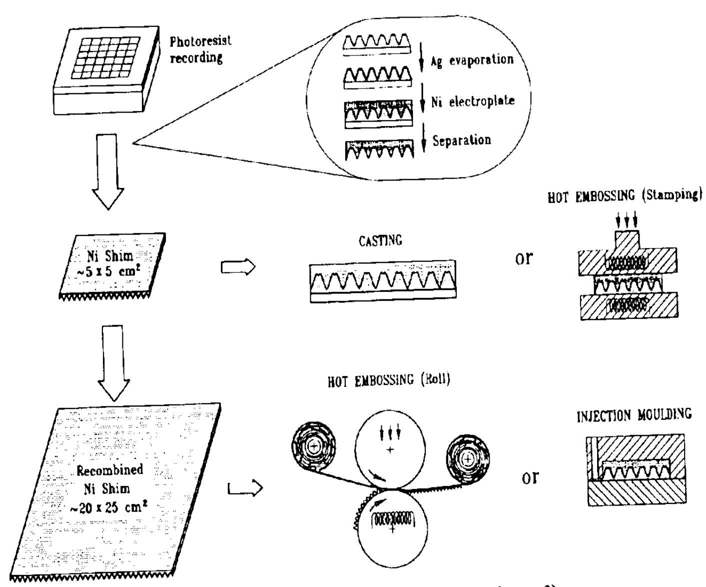



Figure 3 : Replication technologies for surface-relief DOE microstructures (from Reference 3)

processes). Microstructures requiring higher precision are written in arrays with typically a 2% step in exposure and the best microstructure is selected after development.

A second important limitation is the roughness of the fabricated surface. The main source of roughness is line positioning errors during the writing process (in other words, the dynamic positioning accuracy of the xy table). The magnitude of the roughness depends upon the line spacing and the size of the writing spot, and can be minimised by choosing the latter as large as possible for a given microstructure. Typical spot diameters (1/e intensity points) are 1.5 μm (1 μm line spacing) for high resolution microstructures such as multi-segment Fresnel microlenses and 8 μm (2 μm line spacing) for less demanding DOEs such as fan-out kinoforms. The measured roughness for typical DOEs written with these spot sizes is about 20 nm and <5 nm rms respectively.

These sources of error are of experimental origin and of significantly larger magnitude than inherent limitations such as the natural roughness of the developed resist surface or the fidelity of the replication process. They are being reduced by ongoing improvements in the writing system, such as the upgrade to a more accurate positioning system and the introduction of automatic (monitored) development.

**Replication**

A major attraction of surface-relief (planar) DOE microstructures lies in the potential of mass-production by replication technology (Figure 3). This technology is already well established for the production of diffractive foil, display holograms and holographic security features (6), for which microrelief structure up to a maximum depth of about 1 μm is produced in rolls of plastic up to 1 m wide and thousands of meters in length. Deeper microrelief structures currently require casting and moulding replication techniques. In all cases, the first step is to fabricate a metal (usually Ni) shim by electroplating the surface of the original DOE structure, followed by recombination of a number of small area shims to produce the larger shim (~ 1 m² or larger) required for the replication machinery.

For applications in which the dimensional stability of replica DOEs is a problem, replication can be made by casting into a thin film on a stable substrate. In the laboratory, high quality replicas have been fabricated, for example, by casting into thin films of epo-tek 301-2 epoxy (7) and Norland NOA61 uv-curable adhesive (8).

## EXPERIMENTAL RESULTS

In this section, we will give examples of DOEs recently fabricated using the technology described above. In some cases, elements fabricated in resist were sufficient for the application or investigation envisaged. In other cases, replicas in plastic film or in epoxy on glass were fabricated from Ni-shims.

### Fan-out kinoforms

Continuous-relief kinoform microstructures offer a very attractive alternative to binary optical (multilevel) elements for high performance fan-out elements required in applications such as optical computing and parallel processing systems. They are, in general, capable of offering higher efficiency and better uniformity than typical state-of-the-art binary optical elements.

2-dimensional kinoform 9x9 fan-out elements have been fabricated in resist and replicated into epoxy (9). The performance was excellent - measured efficiency for resist recordings (after correction for reflection losses) was better than 94% and overall uniformity better than $\pm 8$ % of the average spot intensity; replicas in epoxy had the same efficiency and a uniformity of $\pm 15$ % (the lower uniformity being due to a known error in the recording of the corresponding relief structure). The kinoform design (computed at IMT, University of Neuchâtel) and an AFM image of the central portion of a fabricated microstructure are shown in Figure 5.

### Phase-Matched Fresnel Elements

Phase Matched Fresnel Elements (PMFEs) are a class of DOE combining the advantages of geometrical and diffractive optical components (5). In a typical microstructure design, the continuous-relief Fresnel segments have lateral sizes down to about 5 μm, with profiles and height steps optimised to maintain proper phase relationships at the design wavelength. PMFEs offer considerable functional flexibility, with typical applications in imaging, illumination and other microoptical systems.

PMFE microstructures have been recorded and replicated into PVC and Polycarbonate film (5). Figure 6 shows the basic PMFE microstructure and an AFM surface profile measurement of an element replicated into polycarbonate.

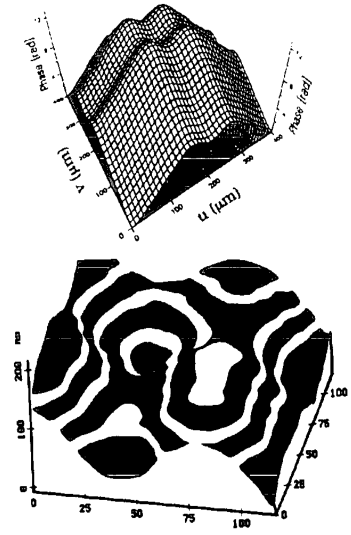



Figure 5 : Computed design (top) and section of fabricated microstructure (bottom) for 9x9 fan-out continuous-relief kinoform (from Reference 9)

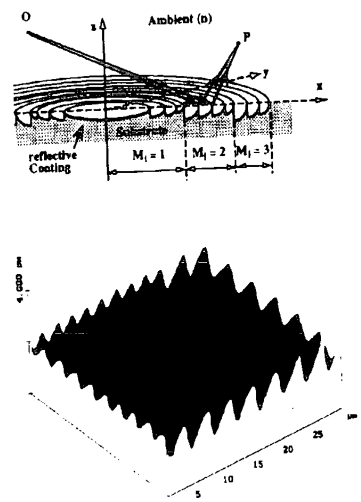



Figure 6 : Phase-matched Fresnel element - schematic (top) and AFM image of a section of an element fabricated in photoresist (bottom).

### MTF control DOEs

DOEs with non-periodic phase structures have been fabricated for applications as low-pass filters and other MTF control filters in optical processing systems. Optical filters with a Gaussian Point Spread Function were fabricated as surface-relief structures and incorporated into liquid crystal cells to produce electrically switchable optical filters (10). Typical surface-relief structures for this application have a maximum relief modulation of up to 7 μm and are fabricated in arrays of 8x8 elements of 1.6 x 1.6 $mm^2$ size.

### Microlens arrays

Arrays of refractive microlenses and of DOE and Fresnel microlenses have been fabricated for a variety of applications. Lenslets have typical diameters of 100 - 500 μm, with essentially zero dead space between lenslets. Replica structures are fabricated as arrays in optical quality epoxy (epo-tek 301-2) on glass substrates, producing high quality elements of good mechanical stability.

## CONCLUSIONS

Continuous-relief DOEs can be fabricated by laser writing in photoresist and replicated by casting or embossing from a Ni shim. The basic technology is operating in the laboratory at PSIZ, with the aim of fabricating both experimental DOE microstructures as well as the master reliefs required for interfacing to industrial production facilities. The quality of the fabricated continuous-reliefs is sufficient for many applications; improvements in the surface roughness can be expected to result from current work on upgrading the experimental writing system.

These DOEs offer an attractive alternative to binary optical DOEs, with new optical properties and, in many cases, with significant improvement in optical performance. The main challenge is in the accurate fabrication of the required continuous-relief microstructure; once this has been achieved, the microstructure can be replicated by a number of existing replication technologies.

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